Search for three-nucleon force effects in two-body photodisintegration of ^{3}He (^{3}H) and in the time reversed proton-deuteron radiative capture process

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Faddeev calculations have been performed for nucleon-deuteron photodisintegration of ^{3}He (^{3}H) and proton-deuteron radiative capture. The bulk of the results is based on the AV18 nucleon-nucleon force and the Urbana IX three-nucleon force together with explicit exchange currents or applying the Siegert approach. Three-nucleon force effects are predicted for both processes and are qualitatively supported by available data.

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I. INTRODUCTION

Three-nucleon ($3N$) forces come more and more into the focus of few-nucleon studies. Pure $3N$ continuum measurements at the accelerator facilities IUCF [1], KVI [2], RIKEN [3], and RCNP [4] are performed around 100–200 MeV nucleon laboratory energies with the aim to confront data to theoretical predictions based on modern high-precision nucleon-nucleon (*NN*) forces only [5]. Clear-cut discrepancies for certain $3N$ observables against all those predictions can be considered to be good candidates for $3N$ force (3NF) effects. Thereby the theoretical investigations are based on numerically precise solutions of the $3N$ Faddeev equations. Then adding present day 3NF models and comparing to those data one tries to explore their strength and spin structure [6]. Right now these 3NF models are the 2π-exchange Tucson Melbourne (TM) [7], a modified version thereof, TM′ [8], which is closer to chiral symmetry, and the Urbana IX [9] forces. Another path to learn about 3NF's is the study of the low lying spectra of light nuclei, as performed in Greens function Monte Carlo calculations [10]. The inclusion of 3π-exchange ring diagrams with intermediate Δ's on top of the Urbana IX 3NF appears to be rather promising to improve the theoretical description of the spectra [11]. In all those investigations there is clear evidence found that present day *NN* forces alone fail to describe many of the studied observables and adding the presently available three-nucleon force models moves theory in the right direction.

A recent approach towards nuclear dynamics is based on chiral perturbation theory, which is closely linked to QCD and develops nuclear forces in a systematic and controlled manner [12]. In that scheme which treats multipion exchanges explicitly and incorporates short range processes in the form of contact forces of increasing chiral dimensions also $3N$ forces are predicted consistently to *NN* forces. In Ref. [13] it has been demonstrated that, like in the conventional approaches mentioned above, $3N$ forces are unavoidable to predict binding energies of three- and four-nucleon nuclei as well as to remove discrepancies in certain $3N$ scattering observables.

Electromagnetically induced reactions in the $3N$ system should also show effects of 3NF's. Since both $3N$ bound and scattering states enter into the nuclear matrix elements for photon induced processes and both types of states are affected by $3N$ forces, it would be surprising if the various response functions for these reactions would be unaffected. In principle, just by the continuity equation $3N$ forces lead also unavoidably to $3N$ currents. It is a quantitative question based on current choices of nuclear force models to reveal signatures by switching on and off $3N$ forces. If certain observables are linked to binding energies and if all modern *NN* forces including the most recent ones based on chiral perturbation theory are unable to predict the experimental bound state energies, but the inclusion of $3N$ forces is, we leave it to the reader to decide whether the changes in those observables are called $3N$ force effects or just binding effects. Apparently, under these circumstances both are tightly bound together. It is only with oversimplified toy model *NN* forces which do not describe the rich *NN* dataset that experimental bound state energies can possibly be achieved. Conclusions based on those models should be taken with caution. The search for three-nucleon force effects in electromagnetically induced processes has been started before. For recent references see Refs. [14–17]. It is the aim of this paper to investigate the nucleon-deuteron (*nd*) photodisintegration of ^{3}He and ^{3}H as well as the time reversed proton-deuteron (*pd*) capture process using modern *NN* forces and various 3NF models.

The single nucleon current operator is supplemented by exchange currents either in the form of the Siegert approximation or by explicitly including meson exchange currents (MECs) of the π- and ρ-like nature. The treatment is carried through nonrelativistically, though presumably some of the data that we analyze, require at least relativistic corrections.

Two-body photodisintegration of ^{3}He (^{3}H) has a long history. Barbour and Phillips [18] found that the incorporation of the interacting $3N$ continuum is crucial for the understanding of that process. They solved the $3N$ Faddeev equations, at that time of course based on simple finite rank forces. This was taken up again more consistently by Gibson and Lehman [19], treating the $3N$ bound state and the final $3N$ continuum on equal footing. More recently, the Bonn group [20,21] used more modern *NN* forces represented in finite rank form. They analyzed quite a few data and pointed out a correlation between a certain cross section peak height and the triton binding energy, an issue that we shall also address, but now in the context of 3NF effects. All the work mentioned relied on the Siegert approximation. The current was restricted to the dominant E_1 multipole [20] or to the E_1 and E_2 multipoles [21]. In a recent paper [22] a benchmark was set on the total $3N$ photodisintegration cross section. There two quite different approaches, the Faddeev one and a hyperspherical harmonic expansion together with the Lorentz integral transform method, were compared to each other using AV18 together with Urbana IX and reached a very good agreement. This documents the technical maturity of advanced present day approaches.

Also for the pd capture process, many experimental and theoretical studies have been performed in the past. We refer to Refs. [21,23,24] for references. Specifically, we want to point to the theoretical investigations by Schadow *et al.* [21], Fonseca and Lehman [25], and to recent studies at very low energies by Viviani *et al.* [26].

The present investigation is restricted to nucleon-deuteron fragmentations in relation to ^{3}He (^{3}H) and we refer to a forthcoming study for $3N$ fragmentations.

The paper is organized as follows. In Sec. II we briefly review our formalism and the dynamical ingredients. Our results for Nd photodisintegration are presented in Sec. III together with available data. The pd capture observables are discussed in Sec. IV. We summarize in Sec. V.

II. FORMALISM

We evaluated photodisintegration and pd capture before in Ref. [24] and Refs. [27,28], always using Faddeev-like integral equations. In Ref. [28] we formulated pd capture based on *NN* forces alone. There the Faddeev-like integral equation is identical to the one for Nd scattering. This is because in pd capture the $3N$ scattering state $|\Psi^{(+)}\rangle$ enters directly. On the other hand, in ^{3}He photodisintegration the $3N$ scattering state $\langle\Psi^{(-)}|$ is involved like in electrodisintegration of ^{3}He. The way to derive Faddeev-like integral equations in the latter cases is to apply the adjoint Moeller wave operator entering the nuclear matrix element to the right, namely, onto the electromagnetic current operator and the ^{3}He bound state [29]. This has the very big advantage that the driving term of that Faddeev-type integral equation is fully connected, namely, proportional to the ^{3}He bound state. Because of the formal identity of the nuclear matrix elements for photodisintegration and electron induced processes, the same Faddeev-like integral equation is applicable. In the two cases, only the components of the current operator in the driving term have to be chosen appropriately. Now using time reversal symmetry one can relate the matrix elements for pd capture and photodisintegration, which are evaluated quite differently. This is a highly nontrivial numerical test for the various complex numerical steps involved.

In Ref. [24] we added a 3NF in the evaluation of the *pd* capture process and applied it to cross sections and several spin observables. The formalism was straightforward since we could use directly the Faddeev-like integral equation for *nd* scattering including $3N$ forces as derived in Ref. [30]. In the same paper [24] we compared Siegert approximation to the explicit use of a restricted but possibly dominant set of mesonic exchange currents.

Now for two- and three-body photodisintegration we would also like to formulate an extension including $3N$ forces. We shall proceed as follows. The nuclear matrix element for *nd* photodisintegration of a $3N$ bound state has the following form:

$$N_\tau^{nd} \equiv \langle \Psi_{\vec{q}}^{(-)} | j_\tau(\vec{Q}) | \Psi_{\rm bound} \rangle, \tag{1}$$

where $\vec{q}$ is the asymptotic relative momentum between the proton and the deuteron, and $j_\tau(\vec{Q})$ is the component of the $3N$ current operator. The scattering state $\langle \Psi_{\vec{q}}^{(-)}|$ can be Faddeev decomposed,

$$\langle \Psi_{\vec{q}}^{(-)}| = \langle \psi_{\vec{q}}^{(-)}|(1+P), \tag{2}$$

where P, according to our standard notation [31], is the sum of a cyclical and an anticyclical permutation. The Faddeev amplitude $\langle \psi_{\vec{q}}^{(-)}|$ obeys the Faddeev equation [30]

$$\langle \psi_{\vec{q}}^{(-)}| = \langle \phi_{\vec{q}}| + \langle \psi_{\vec{q}}^{(-)}|[PtG_0 + (1+P)V_4^{(1)}G_0(tG_0+1)]. \tag{3}$$

Here the channel state $\langle \phi_{\vec{q}}|$ enters, which is a product of a deuteron wave function and a momentum eigenstate of the remaining nucleon. t is the NN t operator acting on nucleons 2 and 3; G_0 is the free $3N$ propagator; P the permutation operator; and $V_4^{(1)}$ the part of a $3N$ force, which singles out particle 1. For our notation see Refs. [5,31].

Using Eqs. (1), (2), and (3) we can write the nuclear matrix element as

$$N_\tau^{nd} = \langle \phi_{\vec{q}}|(1-K)^{-1}(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle, \tag{4}$$

where K is the kernel of the integral equation (3). We introduce

$$|U\rangle \equiv (1-K)^{-1}(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle \tag{5}$$

or explicitly the integral equation

$$|U\rangle = (1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle + [PtG_0 + (1+P)V_4^{(1)}G_0(tG_0+1)]|U\rangle. \tag{6}$$

This form is not yet suitable for numerical applications because of the presence of P to the very left. This has already been noted at the very beginning of our numerical $3N$ studies using nuclear forces without finite rank representations [32]. To rewrite Eq. (6) in a suitable form we use the following obvious identities:

$$(1+P) = \frac{1}{2}P(1+P), \tag{7}$$

$$\frac{1}{2}P(P-1) = 1 \tag{8}$$

and obtain

$$(P-1)|U\rangle=(P-1)(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle +(P-1)P\left(tG_0+\frac{1}{2}(1+P)V_4^{(1)}G_0(tG_0+1)\right) \times\frac{1}{2}P(P-1)|U\rangle. \tag{9}$$

This Faddeev-like integral equation is suitable for numerical implementations and has the form

$$|\tilde{U}\rangle=(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle +\left(tG_0P+\frac{1}{2}(1+P)V_4^{(1)}G_0(tG_0+1)P\right)|\tilde{U}\rangle \tag{10}$$

with

$$|\tilde{U}\rangle\equiv(P-1)|U\rangle. \tag{11}$$

Then the nuclear matrix element results as

$$N_\tau^{\rm Nd}=\frac{1}{2}\langle\phi_{\vec{q}}|P|\tilde{U}\rangle. \tag{12}$$

In view of a forthcoming paper we also describe now the treatment of the complete $3N$ breakup process. The nuclear matrix element is

$$N_\tau^{3N}\equiv\langle\Psi_{\vec{p},\vec{q}}^{(-)}|j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle. \tag{13}$$

The asymptotic momenta of the three nucleons are given by standard Jacobi momenta $\vec{p}$ and $\vec{q}$ [31]. The Faddeev amplitude corresponding to the scattering state in Eq. (13) is now defined via

$$\langle\psi_{\vec{p},\vec{q}}^{(-)}|={}^{(-)}\langle\vec{p},\vec{q}|+\langle\psi_{\vec{p},\vec{q}}^{(-)}|K, \tag{14}$$

where K is the same kernel as used before in Eq. (3) and

$${}^{(-)}\langle\vec{p},\vec{q}|\equiv\langle\phi_0|(tG_0+1). \tag{15}$$

It is to be noted that the free two-body subsystem state in $\langle\phi_0|$ is properly antisymmetrized. Here $\langle\phi_0|$ is the free $3N$ state. Following the same steps as above, one ends up with

$$N_\tau^{3N}=\frac{1}{2}\langle\phi_0|(tG_0+1)P|\tilde{U}\rangle, \tag{16}$$

where $|\tilde{U}\rangle$ is as given above.

In the actual numerical calculation, however, we used another form, which we would also like to present here for the purpose of completeness. The reason for that is that at the time of the installation, the very heavy numerical tasks were more easily performed with already existing building blocks. Those alternative forms are for the *nd* breakup,

$$N_\tau^{nd}=\langle\phi_{\vec{q}}|(1+P)|j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle+\langle\phi_{\vec{q}}|P|U'\rangle, \tag{17}$$

and for the $3N$ breakup,

$$N_\tau^{3N}=\langle\phi_0|(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle +\langle\phi_0|tG_0(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle +\langle\phi_0|P|U'\rangle+\langle\phi_0|tG_0P|U'\rangle. \tag{18}$$

The Faddeev-like integral equation for $|U'\rangle$ reads then

$$|U'\rangle=\left(tG_0+\frac{1}{2}(1+P)V_4^{(1)}G_0(tG_0+1)\right) \times(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle +\left(tG_0P+\frac{1}{2}(1+P)V_4^{(1)}G_0(tG_0+1)P\right)|U'\rangle. \tag{19}$$

The equivalence between the matrix elements (12) and (16) on the one hand and Eqs. (17) and (18) on the other hand is demonstrated as follows. From Eqs. (10) and (19) we have

$$\begin{aligned}|\tilde{U}\rangle-|U'\rangle&=(1-K)^{-1}\Big((1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle-tG_0(1+P)\\&\quad\times j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle-\frac{1}{2}(1+P)V_4^{(1)}G_0(tG_0+1)\\&\quad\times(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle\Big)\\&=(1-K)^{-1}\left(1-tG_0-\frac{1}{2}(1+P)V_4^{(1)}G_0(tG_0+1)\right)\\&\quad\times(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle.\end{aligned} \tag{20}$$

Using again Eq. (7) and the form of the kernel K, this is

$$\begin{aligned}|\tilde{U}\rangle-|U'\rangle&=(1-K)^{-1}\frac{1}{2}(P-1+1-K)\\&\quad\times(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle\\&=\frac{1}{2}(1-K)^{-1}(P-1)(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle\\&\quad+\frac{1}{2}(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle\\&=\frac{1}{2}(1-K)^{-1}(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle\\&\quad+\frac{1}{2}(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle\\&\equiv\frac{1}{2}|\tilde{U}\rangle+\frac{1}{2}(1+P)j_\tau(\vec{Q})|\Psi_{\rm bound}\rangle.\end{aligned} \tag{21}$$

Thus

$$\frac{1}{2}|\tilde{U}\rangle - |U'\rangle = \frac{1}{2}(1+P)j_{\tau}(\vec{Q})|\Psi_{\mathrm{bound}}\rangle. \tag{22}$$

Now it is a simple task to verify that the two expressions for the $3N$ breakup amplitude, Eqs. (16) and (18), are identical. This is also true for the two *nd* breakup amplitudes, Eqs. (12) and (17). It is efficient to evaluate also the pd capture process using time reversal in terms of the formalism just described. This is what we do in this paper.

III. RESULTS FOR *pd* (*nd*) PHOTODISINTEGRATION OF ^{3}He (^{3}H)

We use the AV18 *NN* force [33] combined with the Urbana IX $3N$ force [9]. By construction, that force combination describes the ^{3}H binding energy correctly. However, it overbinds slightly the ^{3}He bound state energy by 21 keV [34]. For the convenience of the reader we cite the theoretical binding energies: -7.628 MeV for ^{3}H and AV18 alone, -8.48 by construction including Urbana IX, -6.917 MeV for ^{3}He and AV18 together with the Coulomb force, and -7.739 MeV including in addition Urbana IX. The latter value is to be compared with the experimental value -7.718 MeV which is slightly different, but this should be of no significance for the present studies. Unfortunately, we are still unable to include the Coulomb force into the pd continuum, which causes an inconsistency of unknown magnitude. Of course, at least for the higher energies studied in this paper we expect minor Coulomb force effects, as it is supported by pure *pd* scattering investigations [5]. Our calculations are fully converged by choosing total two-nucleon angular momenta up to $j_{\mathrm{max}}=3$ and total $3N$ angular momenta up to $J_{\mathrm{max}}=15/2$. It turned out to be sufficient to keep the $3N$ force different from zero for total $3N$ angular momenta up to $J=7/2$. The standard nonrelativistic form of the single nucleon current operator [35] is supplemented by exchange currents via the Siegert approximation. We use it in the form as detailed in Ref. [24]. In our treatment electric and magnetic multipoles are kept to a very high order (6–7) and no long wavelength approximation is used. Both ingredients are important as has been shown, for instance, in Ref. [22]. The formalism is performed throughout in momentum space. As is well known, the Siegert approach corrects for many-body currents only in the electric multipoles. Available models for two-body currents should then be added for the magnetic multipoles. This, however, is not yet included in this work. On the other hand, we also use explicit exchange currents of the π- and ρ-like types consistent with the AV18 *NN* force. Again, this is not yet a complete approach since further pieces in the AV18 *NN* force have no counterparts in two-body currents, which would be also required to fulfill the continuity equation. This needs further investigations [36], though the expectations are that with the π- and ρ-like parts the dominant currents are taken into account. If the continuity equation would be fulfilled in relation to all parts of AV18, the Siegert approach with respect to the electric multipoles would be essentially equivalent to these explicit MEC's (except for additional $3N$ force effects included in the Siegert approach and less important terms of higher multipolarities, see Ref. [29]). Our aim here is not to forward the theory of the electromagnetic current operator but to apply what is often called "the standard model of nuclear physics" to the complex two-body photodisintegration or *pd* capture processes, which has not been done before to the best of our knowledge.

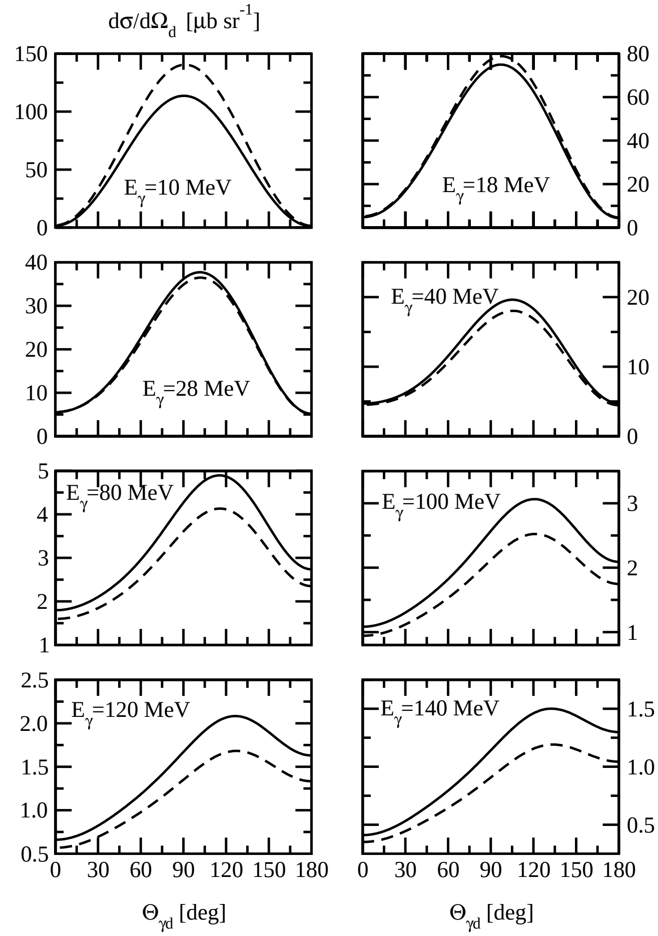

FIG. 1. Deuteron laboratory angular distribution for the process $^3\mathrm{He}(\gamma,d)p$ at different photon energies E_{γ}. Curves show results of calculations with the AV18 *NN* and Urbana IX 3NF forces (solid) and with the AV18 *NN* force alone (dashed). The current is treated in the Siegert approach.

We show in Fig. 1 the angular distribution for pd photodisintegration of ^{3}He against the angle between the outgoing deuteron and the incoming photon direction in the laboratory system. The photon energies E_{γ} vary between 10 and 140 MeV. At the two lower energies the cross section maximum is decreased by adding the 3NF. A related effect has been seen before in Ref. [20] using different *NN* forces. Thereby it was found that with increasing binding energy the value of the maximum decreased. This can be considered as a scaling behavior with the $3N$ binding energy. It ceases to be valid for the higher energies, where the results including the $3N$ force overtake the ones without. At about $E_{\gamma}=28$ MeV the $3N$ force effects for the process $^3\mathrm{He}(\gamma,d)p$ in that observable vanish. In relation to that scaling at low energies one can ask

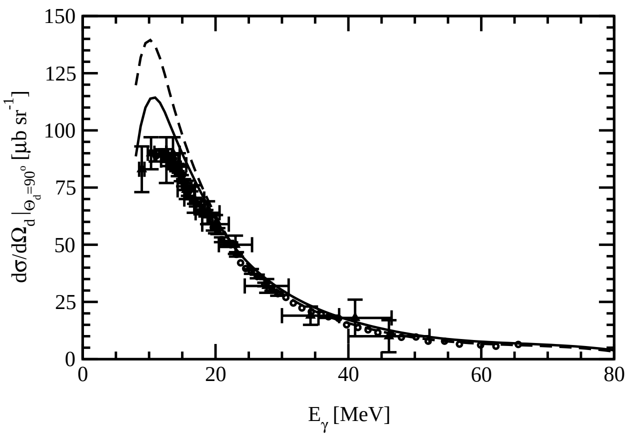

FIG. 2. Deuteron angular distribution for the process ^{3}He$(\gamma,d)p$ at the given deuteron angle as a function of the photon energy E_γ. Curves as in Fig. 1. Since the kinematic shift from the laboratory to the c.m. system is not significant, we combine the data for the 90° laboratory angle (full dots with horizontal and vertical error bars [39]) with the ones for the 90° c.m. angle (open circles [38]).

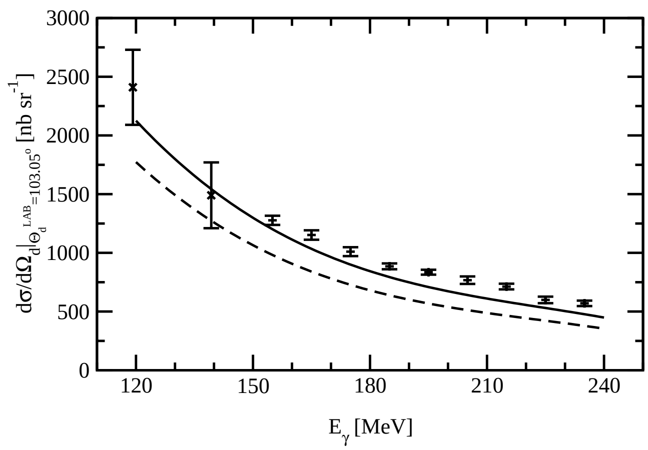

FIG. 3. Deuteron angular distribution for the process ^{3}He$(\gamma,d)p$ at given laboratory angle as a function of the photon energy E_γ. Curves show results of calculations with the AV18 *NN* and Urbana IX 3NF forces (solid) and with the AV18 *NN* force alone (dashed). Explicit π- and ρ-like MEC's are included in the current operator. Data are from Refs. [40] (+) and [41] (×).

the question whether the 3*N* force contributions in the continuum are critical for that result. To that aim we performed calculations where we switched off the 3*N* force in the continuum but kept it in the ^{3}He bound state. Thereby the ^{3}He binding energy did not change. (Note that this is not a consistent calculation and necessarily induces spurious effects.) The effect is a decrease of the cross section of about 16% at $E_\gamma = 100$ MeV in relation to the difference of the results when the 3*N* force is dropped totally. At $E_\gamma = 10$ MeV the presence or absence of the 3NF in the continuum had only a very tiny effect. Nevertheless, we would like to repeat that the correct binding energy could only be achieved by adding the 3NF to the current most modern *NN* forces. In Ref. [37] energy weighted sum rules for the $A=3$ photodisintegration cross sections based on the electric dipole operator have been investigated. They link the energy dependence of the cross section through the integrals to expectation values of the ground state wave functions, which are affected by the 3*N* forces and consequently depend on the binding energy. It appears worthwhile to check the assumptions and approximations in Ref. [37] from the point of view of present day forces, wave functions, and currents.

Have these effects already been seen in some data? We are aware of cross section data at the deuteron laboratory and center of mass (c.m.) angles of 90° as a function of E_γ [39,38]. They are shown in Fig. 2 in comparison to our theoretical results. We see the crossing of the theoretical curves without and with 3NF's around 25 MeV and indeed the data support the decrease of the cross section at lower energy values, as predicted by including the 3NF. At higher energies the effects of the 3NF appear to be somewhat too strong in case of the data of Ticcioni *et al.* [38]. It is possible that the overshooting of the theory at the lowest energies is partially due to the neglection of the pd Coulomb force effects in the continuum. Precise new data would be very welcome.

For $E_\gamma = 120$ MeV and higher photon energies we are aware of another set of data for that process [40,41]. The deuteron laboratory angle is 103° now. In this case the addition of the 3NF is clearly supported by the data. This is shown in Fig. 3. In this case we used the explicit π- and ρ-like MEC's since the energies are higher and Siegert as a low energy approximation is less suited.

There are also total *nd* and *pd* cross section data for the processes ^{3}H$(\gamma,d)n$ and ^{3}He$(\gamma,d)p$. We show them in Figs. 4 and 5 based on the Siegert approach. Clearly the old data for the *nd* cross section have too big error bars to be conclusive. In the case of the *pd* cross section the inclusion of the 3NF's deteriorates the agreement somewhat for the low photon energies. The *nd* cross section data have been displayed before in Ref. [22].

Summarizing, the comparison with the angular distribution data appears to be in qualitative agreement. New im-

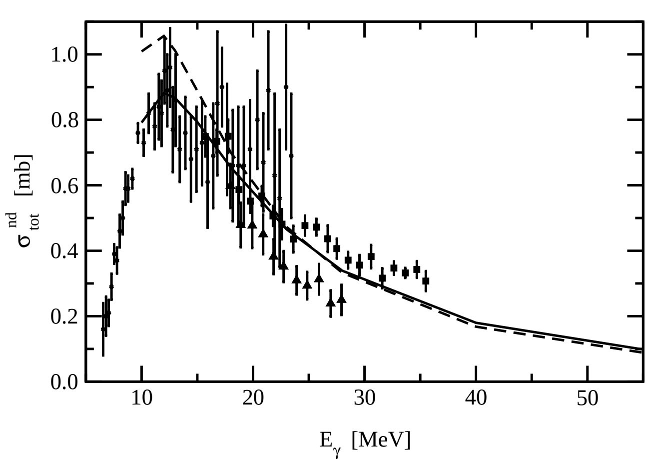

FIG. 4. Total cross section for the process ^{3}H$(\gamma,d)n$ as a function of the photon laboratory energy E_γ. Curves as in Fig. 1. Data are from Refs. [42] (crosses), [43] (squares), and [44] (triangles).

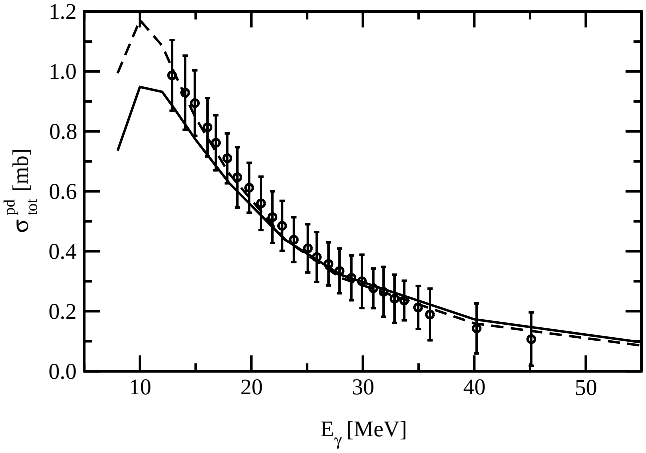

FIG. 5. Total cross sections for the ^{3}He$(\gamma,d)p$ process as a function of the photon laboratory energy E_γ. Curves as in Fig. 1. Data are from Ref. [45].

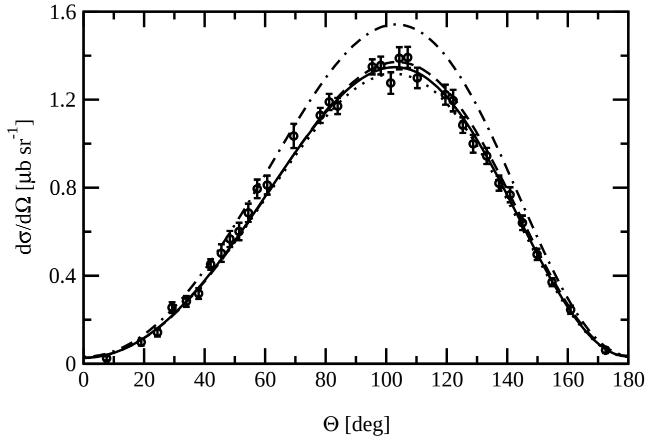

FIG. 6. The photon angular distribution for *pd* capture at $E_d = 19.8$ MeV against the c.m. γ-d scattering angle. The curves describe the Siegert (dashed-dotted), the single nucleon plus MEC (dashed), Siegert with 3NF (dotted), and the single nucleon plus MEC with 3NF (solid). These four cases are called a, b, a', and b' in the text. Data are from Ref. [46].

proved data would be welcome and a more refined treatment of two-body currents is required.

In order to provide information on the dependence of the cross sections on the choice of forces and currents we display in Table I results for the total two-body photodisintegration cross section of ^{3}He (^{3}H) at three energies. At 12 MeV we see 5% (10%) spreads with (without) 3NF's. At the higher energies the spreads are negligible, which points to a certain stability of the results and helps to identify 3N force effects. Precise data, however, would be required.

IV. pd CAPTURE CROSS SECTIONS

In Ref. [24] cross sections and spin observables for pd capture have been investigated at proton laboratory energies E_p between 5 and 200 MeV (corresponding to deuteron laboratory energies E_d between 10 and 400 MeV). The emphasis was on testing the sensitivity of *pd* capture observables to changes in the choice of *NN* forces and to compare the predictions of the Siegert approximation to the ones including explicitly π- and ρ-like MEC's. Please note, as pointed out above, that both approaches in the way we treat them are approximate and therefore the comparison is more of a qualitative nature. We found that at low energies Siegert and MEC predictions are rather close together, whereas at the higher energies differences showed up. In the context of the Siegert approach the predictions based on different *NN* forces turned out to be rather close together, which is a satisfactory result, since it demonstrates stability. The agreement with the data was mostly good, but also clear discrepancies were present, which call for an improvement of the dynamical input. It is the aim of this paper to include 3NF's, which in the previous work were only marginally investigated.

In the following we show our results for cross sections between $E_d = 19.8$ MeV and $E_d = 400$ MeV. In all of the following figures four theoretical curves are displayed. They are based on the Siegert approach, the single nucleon current together with explicit π- and ρ-like MEC's consistent to the *NN* force, the Siegert approach with 3NF, and MEC's with 3NF. Let us denote these four choices by a, b, a', and b', for short.

We see in Fig. 6 the *pd* capture cross section at $E_d = 19.8$ MeV. In both cases, Siegert and explicit MEC's, the inclusion of the 3NF decreases the cross section; in case of Siegert the decrease is much stronger. The choices a', b, and b' are well within the error bars and only a is significantly too high. At $E_d = 95$ MeV the cross section data are fairly well described by all four choices. This is displayed in Fig. 7. As already seen in the *nd* photodisintegration, the theoretical cross section increases by including 3NF's. This is in agreement with our findings for *pd* capture [24].

Finally we show the cross sections for $E_p = 100$, 150, and 200 MeV (corresponding to $E_d = 200$, 300, and 400 MeV) in

TABLE I. The total cross section (in mb) for two-body photodisintegration of ^{3}He (^{3}H).

	$E_\gamma = 12$ (MeV)	$E_\gamma = 40$ (MeV)	$E_\gamma = 120$ (MeV)
AV18-Siegert	1.086 (1.056)	0.160 (0.168)	0.016 (0.015)
AV18-MEC	0.953 (0.949)	0.156 (0.155)	0.017 (0.015)
CD Bonn 2000–Siegert	0.997 (0.980)	0.163 (0.169)	0.017 (0.016)
AV18+Urbana IX–Siegert	0.932 (0.882)	0.173 (0.180)	0.020 (0.018)
AV18+Urbana IX–MEC	0.934 (0.915)	0.172 (0.169)	0.020 (0.017)
CD Bonn 2000+TM′-Siegert	0.917 (0.889)	0.170 (0.176)	0.020 (0.018)

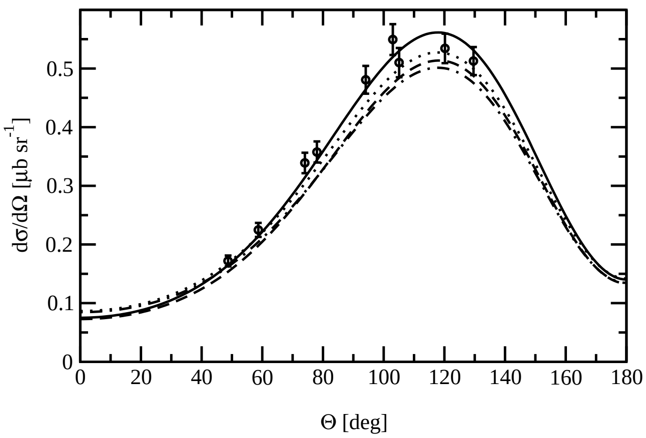

FIG. 7. The same as in Fig. 6, but for $E_d = 95$ MeV. Data are from Ref. [47].

Fig. 8. The cases with the explicit MEC's and 3N forces (b') describe the data best (except for small angles). The choice a clearly underpredicts the maxima.

V. SUMMARY AND CONCLUSIONS

We presented the formalisms for including 3NF's into the Faddeev framework for photodisintegration of three-nucleon bound states. The resulting equations are solved rigorously using high precision nuclear forces: AV18 together with the Urbana IX 3NF or CD Bonn [49] with TM 3NF. Many-body currents are included either in the form of π- and ρ-like exchanges related to AV18 or via the Siegert approach where the latter corrects only electric multipoles for many-body currents and the former does not include all two-body currents consistent with AV18 (in the sense of fulfilling the continuity equation). Thus both ways of going beyond the single nucleon current are approximate but currently used in the literature. The calculations are nonrelativistic but employ state of the art dynamics. We posed several questions. How well do the Siegert approach and the explicit use of the π- and ρ-like MEC's compare with each other? Our results displayed for *pd* capture show differences between the two approaches which calls for improvements either by adding two-body currents for the magnetic multipoles in the Siegert approach or by adding at least the currents beyond the π- and ρ-like parts required for consistency with AV18. Qualitatively, however, the two approaches give similar results.

Another even more central question in this paper was to shed light on possible 3NF effects. In case of *pd* photodisintegration of ^{3}He we compared theoretical predictions without and with a 3NF. We found a clear signature in adding the 3NF. The maxima are decreased at low energies and increased at high energies. The turning point is around $E_\gamma = 28$ MeV. At the low energies this can be considered as a scaling effect with the ^{3}He binding energy but one has to note that based on present day *NN* forces the ^{3}He binding energy can only be achieved if a 3NF is added. These 3N force effects up to about 60 MeV are too small to be verified by the presently available data. However, at the lower energies, E_γ about 10 MeV, our theoretical predictions including 3N forces are clearly too high which might be due to the neglected Coulomb force in the continuum. At the higher energies, $E_\gamma \geqslant 120$ MeV, the effects are larger and qualitatively supported by the data. One should, however, be aware that beyond the π threshold we certainly leave the validity of our nonrelativistic framework. In case of the *pd* capture at the higher energies, $E_\gamma = 100$ MeV and above, explicit use of MEC's together with the 3N force model shows a tendency to move theory better towards the data than without 3N forces. The failure at the smaller angles shows, however, that some ingredients are missing. Overall, we demonstrated that 3NF's can be incorporated into such a complex 3N reaction process and effects are visible related to the models used. An improved theoretical treatment of many-body currents and more precise data are needed to achieve a clearer view towards 3N force effects.

Altogether, the shifts caused by the Urbana IX 3NF on top of the AV18 *NN* force and explicit MEC's are supported by most of the data we analyzed. The Siegert approach is less successful. The use of other force combinations as exemplified in the total two-body photodisintegration cross section does not lead to alarming variations. High quality data would be very helpful to challenge theory more strongly.

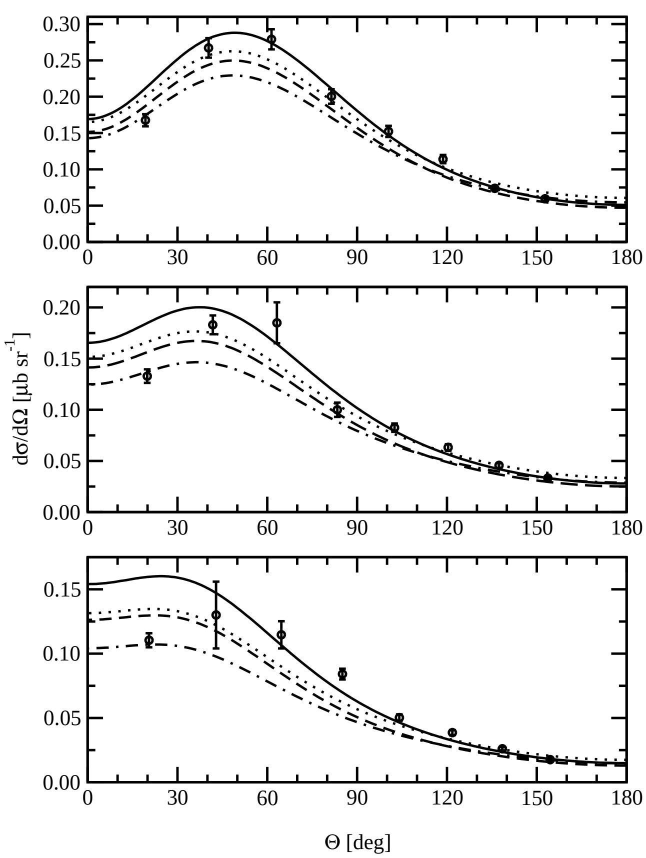

FIG. 8. The photon angular distribution for *pd* capture at three different proton laboratory energies ($E_p = 100$, 150, and 200 MeV from above to below) against the c.m. γ-p scattering angle. Curves as in Fig. 6. Data are from Ref. [48].

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